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Letter to the Editor

Radiative levitation: a likely explanation for pulsations in the unique hot O subdwarf star SDSS J160043.6+074802.9

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ABSTRACT

Context. SDSS J160043.6+074802.9 (J1600+0748 for short) is the only hot sdO star for which unambiguous multiperiodic luminosity variations have been reported so far. These rapid variations, with periods in the range from ~60 s to ~120 s, are best qualitatively explained in terms of pulsational instabilities, but the exact nature of the driving mechanism has remained a puzzle.
Aims. Our primary goal is to examine quantitatively how pulsation modes can be excited in an object such as J1600+0748. Given the failure of uniform-metallicity models as well documented in the recent Ph.D. thesis of C. Rodríguez-López, we consider the effects of radiative levitation on iron as a means to boost the efficiency of the opacity-driving mechanism in models of J1600+0748.
Methods. We combine high sensitivity time-averaged optical spectroscopy and full nonadiabatic calculations to carry out our study. In the first instance, this is used to estimate the location of J1600+0748 in the $\log g - T_{\rm eff}$ plane. Given this essential input, we pulsate stellar models consistent with these atmospheric parameters. We construct both uniform-metallicity models and structures in which the iron abundance is specified by the condition of diffusive equilibrium between gravitational settling and radiative levitation.
Results. On the basis of NTLE H/He synthetic spectra, we find that the target star has the following atmospheric parameters: $\log g = 5.93 \pm 0.11$, $T_{\rm eff} = 71\,070 \pm 2725$ K, and $\log N({\rm He})/N({\rm H}) = -0.85 \pm 0.08$. This takes into account our deconvolution of the spectrum of J1600+0748 as it is polluted by the light of a main sequence companion. We confirm that uniform-metallicity stellar models with Z in the range from 0.02 to 0.10 cannot excite pulsation modes of the kind observed. On the other hand, we find that the inclusion of radiative levitation, as we implemented it, leads to pulsational instabilities in a period range that overlaps with, although it is narrower than, the observed range in J1600+0748. The excited modes correspond to low-order, low-degree p-modes.
Conclusions. We infer that radiative levitation is a likely essential ingredient in the excitation physics at work in J1600+0748.

Key words. stars: oscillations – stars: subdwarfs – stars: individual: SDSS J160043.6+074802.9

1. Astrophysical context

The asteroseismological potential of hot O subdwarf (sdO) stars was first investigated by Cristina Rodríguez-López who wrote an interesting thesis on the topic at the Universidad de Vigo. In that thesis, she presented the results of an observational search for luminosity variations in a sample of 56 sdO stars (Rodríguez-López et al. 2007), as well as the results of a stability survey of representative evolutionary models using a full nonadiabatic approach (Rodríguez-López et al. 2006a,b, 2007). Two potential pulsator candidates came out of that observational search, one with an apparently dominant period of around 500 s (PG 1427+196), and the other with a period of about 100 s (HS 1707+6121). In both cases, however, further observations are needed to confirm the suggested variability, as the available photometric data is not sensitive enough to decide unequivocally of the reality of the phenomenon. More challenging in our view is that none of the models investigated by Rodríguez-López and collaborators were found to excite pulsation modes in the period range suggested by their observations, although a general tendency toward instability has been noted (see, e.g., Rodríguez-López et al. 2006b).

In that context, the unambiguous discovery of short-period (from ~60 s to ~120 s) multiperiodic brightness variations in the relatively faint (g = 17.41) SDSS object J160043.6+074802.9 – J1600+0748 for short in what follows – by Woudt et al. (2006) came as a puzzling surprise. Indeed, although no estimates of the atmospheric parameters of J1600+0748 is provided by Woudt et al. (2006), their SALT spectrum leaves little doubt that it is a spectroscopic binary consisting of a hot sdO and late-type main sequence companion. In addition, the numerous oscillations uncovered by Woudt et al. (2006) in J1600+0748 (some 13 distinct periodicities excluding the harmonic of the dominant one) are best explained in terms of pulsational instabilities in the sdO primary. Indeed, the multiple periods involved and the nature of the secondary (see below) require that this must be the case. The interesting question that arises then is what is the cause of pulsational driving in J1600+0748. In view of the negative results

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found by Rodríguez-López et al. (2006b) in their stability survey, that question becomes even more relevant.

One piece of physics that can potentially be very important, but was not included in the sdO models built by Rodríguez-López and collaborators, is radiative levitation. Indeed, all of their models are uniform-metallicity equilibrium structures, and the competition between gravitational settling and radiative levitation of an opaque element such as iron, for example, has not been taken into account. This remark should in no way be interpreted as a criticism of their excellent work as it is indeed quite difficult, if not downright impracticable, to implement microscopic diffusion (including radiative levitation) in full evolutionary calculations such as those they carried out. In fact, the authors are quite aware of that potential shortcoming in the discussion section of Rodríguez-López et al. (2006b). In pioneering investigations such as instigated by Rodríguez-López et al. (2006a,b, 2007), it is usual to estimate the effects of possible enhancements of the abundances of iron-peak elements in the driving region by using an increased (uniform) metallicity, but at the price of reaching quite unrealistic values such as $Z = 0.10$ and beyond, for example. This has been done by Charpinet et al. (1996) in their first exploratory investigation of the properties of models of short-period pulsating sdB stars. The same strategy was also adopted more recently by Jeffery & Saio (2006) in their discussion of long-period pulsating sdB stars.

We note, after Charpinet et al. (2001) and Fontaine et al. (2006), that this strategy has its limitations. This is particularly true for properly mapping the instability region in the $\log g - T_{\rm eff}$ domain and for finding the correct range of unstable modes in period space. In view of the persistent puzzle posed by the discovery of pulsational instabilities in J1600+0748, we decided to investigate the problem with the help of our so-called second-generation static models that incorporate a nonuniform iron profile as determined by the condition of diffusive equilibrium between gravitational settling and radiative levitation. In the light of the work of Fontaine et al. (2006) on sdB stars based on time-dependent diffusion calculations, we expect that this state of equilibrium is reached over timescales much shorter than typical evolutionary times for sdO stars as well.

2. Spectroscopy and atmospheric parameters

Given that sdO stars are found in a very wide domain of the $\log g - T_{\rm eff}$ plane (from ~4.0 to ~6.5 in $\log g$, and from ~40 000 K to ~100 000 K in $T_{\rm eff}$), it is essential that the location of J1600+0748 be obtained with some accuracy. To this end, we secured a high-sensitivity optical spectrum of the star as illustrated by the top curve in Fig. 1. As first pointed out by Woudt et al. (2006), J1600+0748 is clearly a spectroscopic binary made of a hot sdO star and, most likely, a late-type main sequence companion. The spectrum shown in Fig. 1 is indeed obviously "polluted" by the light of a cool star showing the Ca II K and H doublet at 3934−3968 Å and the Mg I complex at 5167−5184 Å as its most conspicuous features. We went to considerable lengths to determine the most probable spectral type of the companion, by cross-correlating the observed spectrum with numerous main sequence F, G, and K spectrum templates obtained with the same experimental setup. It is notable that the two best-matching G0V templates were superior even to F9 and G1 templates. The results of our efforts are shown by the middle curve of Fig. 1 illustrating our cleansed spectrum, that of the sdO component. It is the result of the subtraction from the original spectrum (top curve) of the appropriately scaled and shifted average of the two G0V spectra (bottom curve).

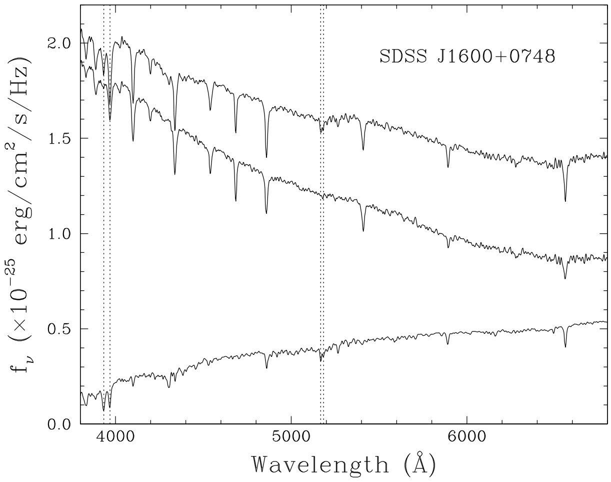

Fig. 1. High-sensitivity ($S/N \sim 300$) optical spectrum of the J1600+0748 system (upper curve) obtained at the Steward Observatory 2.3-m telescope with the B&C spectrograph. The total exposure time is 44 025 s, gathered over four nights (2007 March 28, May 7, 10, and 11). We used a 400/mm 4889 Å grating in first order and a 2.5″ slit, covering the wavelength region 3620−6895 Å at 9 Å resolution. The spectra were wavelength calibrated using 48 non-blended He and Ar lines, and flux calibrated using the standard stars Feige 34 and BD+28 4211, which were observed each night. The middle curve shows the result of our exercise to cleanse the spectrum of the contribution of the late-type main sequence companion (lower curve).

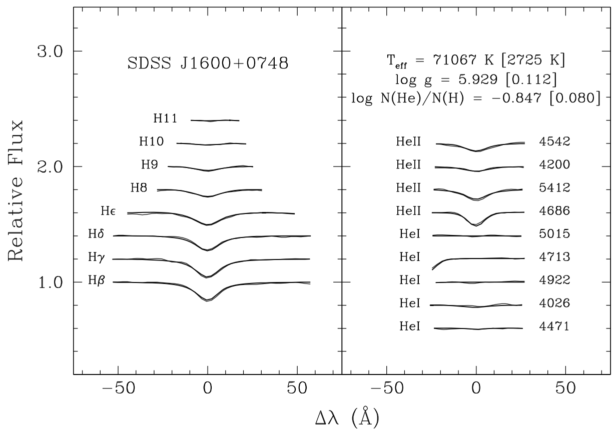

Fig. 2. Model fit (thick curve) of the available hydrogen Balmer lines and helium lines (thin curve) shortward of 5800 Å in our cleansed spectrum of J1600+0748.

A simultaneous fit of the available hydrogen and helium lines shortward of 5800 Å in our cleansed spectrum was performed using synthetic spectra computed from a grid of NLTE H/He model atmospheres. This grid was briefly described in Charpinet et al. (2005), but was recently extended to effective temperatures reaching 100 000 K, thus fully covering the sdO, as well as the sdB, range of interest. Figure 2 shows the result of the fit procedure. We thus estimate that the sdO component of J1600+0748 has $\log g = 5.93 \pm 0.11$, $T_{\rm eff} = 71\,070 \pm 2725$ K, and $\log N({\rm He})/N({\rm H}) = -0.85 \pm 0.08$ (internal errors of the fit only). We suspect that the largest source of uncertainties on these derived atmospheric parameters are systematic effects associated with our neglect of metals in the model atmospheres and synthetic spectra. Currently, those are impossible to quantify.

3. Equilibrium models and stability analysis

We first constructed a reference stellar model defined by the set of parameters: $\log g = 5.93$, $T_{\rm eff} = 71\,000$ K, $M_* = 0.48\ M_\odot$, and $\log q({\rm H}) = -4.0$. These are the quantities needed to specify a second-generation model of a hot subdwarf star (see, e.g., Charpinet et al. 1997). The first two are atmospheric parameters, and these particular values are obviously chosen for consistency with our spectroscopic determination above. A priori we know neither the total mass (M_*) of the sdO primary in J1600+0748 nor the fractional mass (q(H)) contained in its H-rich outer envelope. However, under the plausible assumption that J1600+0748 is a former (binary) sdB star (although it is well known that sdO stars are not necessarily all post-EHB objects), we picked a representative total mass and hydrogen envelope mass appropriate for that earlier evolutionary phase.

To build that model, it was necessary to compute the equilibrium distribution of iron as a function of depth taking radiavite levitation into account and assuming the state of diffusive equilibrium in the envelope layers where the action is concentrated in terms of the driving/damping process. In that, we followed the same prescription as used earlier by Charpinet et al. (1997; see also Charpinet et al. 2001, for more details), but it was necessary to extend the calculations to a much higher effective temperature than those considered in the sdB survey carried out by Charpinet et al. (1997). We recall here that our description of radiative levitation within the context of hot subdwarf stars is simplified in that we consider only iron levitating in a pure hydrogen background. Of course, the real situation has to be more complicated than this, and other elements, particularly other iron-peak elements, must also enter the picture. We justify our approach on the basis of the success we have had with the simplified picture in terms of explaining the properties of short-period pulsating sdB stars (and see Fontaine et al. 2008, for a recent review of achievements and challenges in that field). Finally, to provide a very crude idea of the width of a possible instability strip for sdO stars, we built two similar equilibrium models, one with $T_{\rm eff} = 61\,000$ K and the other with $T_{\rm eff} = 81\,000$ K, all other things being the same. Given that the computations of the iron equilibrium profiles are particularly time-consuming, and keeping in mind the exploratory nature of this work, we felt that it was sufficient here to examine the potential of radiative levitation with this rather limited number of models. For comparison purposes, we also constructed additional models, but with a uniform metallicity in those cases (see below).

In view of the observed period range in J1600+0748, 62.74–119.33 s according to Woudt et al. (2006), we searched our models for all pulsation modes with values of the degree index $\ell = 0$, 1, and 2 in the period range 60–200 s. Given the relatively high gravity involved ($\log g = 5.93$), all of these modes must necessarily be recognized as p-modes at the outset because, as is well known (see, e.g. Charpinet et al. 2000), the lowest-order g-modes have much longer periods than 200 s in a hot subdwarf star with that gravity. Quite interestingly, our nonadiabatic calculations readily revealed pulsational instabilities in our J1600+0748 reference model ($T_{\rm eff} = 71\,000$ K). Details are given in Table 1 where the mode identification (in terms of the degree index ℓ and radial order k), the period P, and the imaginary part of the complex eigenfrequency $\sigma_{\rm I}$ are listed. If the sign of the latter is negative (positive), this implies that the mode of interest is excited (damped). Table 1 then reveals that pulsation modes are excited in a narrow range of period, from ~105 s to ~120 s in this particular model. Moreover, this band of excited periods overlaps with that observed in J1600+0748, although it is distinctly narrower than the latter. This shortcoming should not be cause for great concern at this stage because our implementation of radiative levitation, as discussed above, is a simplified one. The essential result here is that a model of J1600+0748, consistent with the spectrocopic constraints and taking the effects of radiative levitation into account, shows excited modes in the same period range as those observed.

Figure 3 shows the details of the driving/damping process for one of the excited modes ($\ell = 0$, $k = 1$) in our reference model.

Table 1. Nonadiabatic properties for our reference model.

ℓ	k	P (s)	$\sigma_{\rm I}$ (rad/s)	stability
0	5	64.99	$+1.527\times10^{-3}$	yes
0	4	82.86	$+1.875\times10^{-3}$	yes
0	3	94.35	$+1.952\times10^{-3}$	yes
0	2	106.14	-9.861×10^{-4}	no
0	1	119.38	-6.461×10^{-4}	no
0	0	163.60	$+1.144\times10^{-5}$	yes
1	6	64.69	$+1.556\times10^{-3}$	yes
1	5	82.58	$+1.908\times10^{-3}$	yes
1	4	94.08	$+1.101\times10^{-3}$	yes
1	3	105.92	-9.587×10^{-4}	no
1	2	119.03	-6.688×10^{-4}	no
1	1	162.21	$+1.225\times10^{-5}$	yes
2	6	63.91	$+1.556\times10^{-3}$	yes
2	5	70.83	$+6.235\times10^{-4}$	yes
2	4	82.52	$+1.881\times10^{-3}$	yes
2	3	93.33	$+2.200\times10^{-3}$	yes
2	2	105.23	-9.037×10^{-4}	no
2	1	118.21	-7.289×10^{-4}	no
2	0	158.49	$+1.471\times10^{-5}$	yes

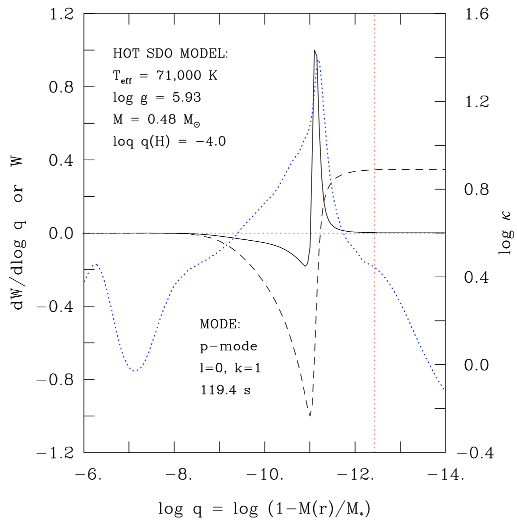

Fig. 3. Details of the driving/damping process for an excited mode in our reference model of J1600+0748. The solid curve shows the integrand of the work integral of the mode as a function of fractional mass depth. The dashed curve shows the running work integral W, from left to right, toward the surface of the model. The final positive value of the work integral at the surface indicates that the mode is globally excited. The blue dotted curve gives the run of the Rosseland opacity, to be read on the RHS axis. The primary maximum in the opacity profile, located at $\log q \simeq -11.2$ and corresponding to a temperature $T \simeq 1.78\times10^5$ K, is caused by the partial ionization of the M-shell electrons in levitating iron. The vertical red dotted line gives the location of the photosphere at $\tau_{\rm R} = 2/3$.

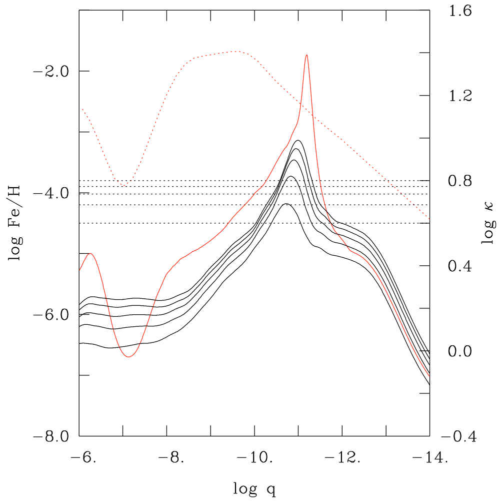

Fig. 4. Iron-to-hydrogen number ratio (dotted curve) and Rosseland opacity (solid curve) profile in the envelope of representative stellar models. The black curves refer to models with uniform metallicity specified by Z = 0.02, 0.04, 0.06, 0.08, and 0.10, *from bottom to top*. The red curves refer to our reference model that takes radiative levitation into account.

The near coincidence of the maximum in the opacity distribution with maximum local driving is the signature of a classical κ-mechanism, similar to the one found in pulsating sdB stars. It is also useful to point out that no instabilities were found in our $T_{\rm eff}$ = 61 000 K model, while a narrower band of periods (only a single mode instead of two is driven for a given ℓ family) is excited in our $T_{\rm eff}$ = 81 000 K model. This strongly suggests the existence of an sdO instability island in the $\log g - T_{\rm eff}$ plane, distinct and separated from the instability strip for short-period pulsating sdB stars (see, e.g., Fig. 9 of Charpinet et al. 2001). This clearly deserves further investigation.

We also pulsated models with the same defining parameters as those of our reference model, but using a uniform metallicity throughout. We considered five different values of the metallicity parameter, Z = 0.02, 0.04, 0.06, 0.08, and 0.10. None of the models thus constructed showed pulsational instabilities. This is in line with the negative results found by Rodríguez-López et al. (2006a,b, 2007). Figure 4 clearly shows that the opacity peak produced by radiative levitation is stronger and sharper (remember that the opacity derivatives play a key role in the κ-mechanism) than those obtained in uniform-metallicity models. The general tendency toward instability noted by Rodríguez-López et al. (2006b) is hence pushed over into the true instability regime, thanks to the effects of radiative levitation.

4. Conclusion

Our exploratory study has revealed that low-order, low-degree p-modes can be excited in a model of J1600+0748 that takes the effects of radiative levitation into account. The band of predicted excited periods is narrower than what is observed in the real star, but it has high value of overlapping with it. At the same time, our work confirms the results of Rodríguez-López et al. (2006a,b, 2007) to the effect that uniform-metallicity models (with values of Z as high as 0.10) are unable to drive pulsation modes in the regime of interest. We thus conclude that radiative levitation is the key mechanism behind the existence of pulsational instabilities in the sdO component of J1600+0748.

Table 2. Tentative mode identification for J1600+0748.

ℓ	k	$P_{\rm th}$ (s)	$P_{\rm obs}$ (s)	$A_{\rm obs}$ (mmag)
0	5	67.06	70.48	4.8
0	4	77.15	76.61	3.4
0	3	92.24	...	...
0	2	105.64	110.01	6.8
0	1	118.43	119.33	39.8
1	5	76.74	76.50	2.2
1	4	91.38	...	...
1	3	105.48	103.61	4.0
1	2	118.15	118.17	4.8
2	6	65.79	62.74	3.0
2	5	73.32	73.14	2.6
2	4	77.69	79.83	2.4
2	3	91.30	...	...
2	2	104.67	102.00	2.8
2	1	117.47	117.95, 117.42	2.5, 2.2

We end our discussion by adding that we also explored the vicinity of our reference model in the $\log g - T_{\rm eff}$ plane to see if some reasonable period match could be obtained between predicted and observed periods, given the rich observed spectrum in J1600+0748 (Woudt et al. 2006). By forcing the 12 observed independent periodicities to belong to modes with ℓ = 0, 1, or 2, and by searching only in the 2D space defined by the $\log g - T_{\rm eff}$ plane, we obtained the results summarized in Table 2. The optimal model that we found is defined by $\log g$ = 5.94, $T_{\rm eff}$ = 69 500 K, M_* = 0.48 $M_\odot$, and $\log q$(H) = –4.0. Note that our search was done in the adiabatic approximation and that we kept the same Fe profile appropriate for $T_{\rm eff}$ = 71 000 K alone, so this is necessarily an approximate approach. Still, without optimization in the M_* and $\log q$(H) directions, we get a very plausible result, with ample room for improvement. The amplitude hiearchy in terms of ℓ is particularly suggestive.

References

Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 1996, ApJ, 471, L103
Charpinet, S., Fontaine, G., Brassard, P., et al. 1997, ApJ, 483, L123
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 2000, ApJS, 131, 223
Charpinet, S., Fontaine, G., & Brassard, P. 2001, PASP, 113, 775
Charpinet, S., Fontaine, G., Brassard, P., et al. 2005, A&A, 437, 575
Fontaine, G., Brassard, P., Charpinet, S., & Chayer, P. 2006, Mem. Soc. Astron. Ital., 77, 49
Fontaine, G., Brassard, P., Charpinet, S., et al. 2008, in Hot Subdwarf Stars and Related Objects, ASPC, ed. Uy. Heber, R. Napiwotzki, & C. S. Jeffery, in press
Jeffery, C. S., & Saio, H. 2006, MNRAS, 372, L48
Rodríguez-López, C., Moya, A., Garrido, R., et al. 2006a, Bal. Astron., 15, 313
Rodríguez-López, C., Garrido, R., Moya, A., et al. 2006b, LNEA, 2, 167
Rodríguez-López, C., Ulla, A., & Garrido, R. 2007, MNRAS, 379, 1123
Rodríguez-López, C., Garrido, R., Moya, A., et al. 2007, Comm. Astero., 150, 273
Woudt, P. A., Kilkenny, D., Ziestman, E., et al. 2006, MNRAS, 371, 1497